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Analysis of HEMCL Railgun Insulator Damage

Paul J. Cote, Mark A. Johnson, Krystyna Truszkowska, Stephen B. Smith, and Mark Fleszar

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Analysis of HEMCL Railgun Insulator Damage

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Abstract

Severe insulator damage is regularly observed near the one meter location and beyond in recent high energy, high current tests in a 4 meter railgun. Analyses of the damaged insulator surfaces were conducted to determine the source of this damage. Laser pulse heating tests were performed to simulate effects observed on the insulators.

The analyses show that the primary damage to the insulators is in the form of epoxy pyrolysis, and glass fiber softening and liquification. It is concluded that the damage source is plasma heating. Plasmas are expected in these systems because of the presence of high rail-to-rail voltages behind the armature; the magnitude of these voltages reaches peak values near the one meter location where the damage is most severe. In an earlier study, severe thermal damage was found on the steel rail surfaces adjacent to the damaged insulators; this damage was also attributed to plasma heating.

Keywords: Railguns, insulator, pyrolysis, epoxy, glass fibers, plasmas, liquification, melting.

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Introduction

Gee and Persad [1] studied the damage of G10 insulators in a 7 meter medium caliber (4mm square bore) railgun. The progress of the degradation was monitored during a 10 shot sequence of firings. The peak rail current listed is 940 kA. They observed degradation in the form of thermally induced sublimation of the thermosetting epoxy matrix which is followed by mechanical removal of the newly exposed woven glass fibers. Regions with the highest combined peak muzzle voltage and peak current showed the highest degradation. Their muzzle voltage traces show that the zones of high degradation are in the transition region (the location where the armature/rail contact has changed from a liquid metal film to a plasma brush) indicating that the main source of damage is plasma heating.

The present study is on a 0.7 m section of insulator taken from the most severely damaged section of a G10 insulator in a 4 meter railgun. An earlier study [2] was conducted on the metal rail liner erosion in the same railgun which produced the present damage on the adjacent G10 insulators. The railgun is a high energy medium caliber railgun launcher (HEMCL) where the copper rails are lined with Glidcop and steel. Two primary rail surface erosion mechanisms are observed: a.) groove formation from metal rail surface melting due to localized, pinched, currents flowing through the liquid armature/rail interface, and, b.) generalized, relatively uniform surface melting of the steel rails with heat affected zones beneath the melt layer. The generalized, uniform surface melting is attributed to plasma formation behind the armature as a result of high fields that result as a consequence of induced emfs. Unlike the Gee and Persad study, transition to a plasma brush does not occur in the present tests (as determined by the muzzle voltage traces) so transition is not the plasma source here. Instead, the emfs responsible for the high fields that tend to generate plasmas behind the armature originate from rapid changes in rail current and from the motion of the armature. A theoretical treatment of these induced emfs is presented in reference [3].

A similar analysis of rail erosion data from a 1.1 MA railgun system [5] led to essentially the same conclusions that we obtained in reference [2] regarding the origin of the rail damage and the likelihood of rail-to-rail plasmas. From the present observations of pyrolytic epoxy degradation and glass fiber softening and liquification in the insulator, it is determined that rail-to-rail plasmas are present behind the armature.

Experimental

The 0.7 meter G10 specimen, shown schematically in Figure 1, was obtained from a railgun test in the HEMCL system at the Institute for Advanced Technology, in Austin TX. G10 is a composite comprised of E-glass fibers in an epoxy matrix. The G10 specimen was removed from the gun after firing three solid aluminum armatures. In these experiments, the two 4 meter long copper rails of the EM gun were lined with GlidCop Al-25 plate over first ~one meter length of rail and with AISI 4130 steel plate over the remaining ~3 meters of rail length. The liner width and thickness are 4.1 cm and 0.3 cm respectively. Peak currents were approximately 1.6 MA.

Included in the present study are results from laser pulsing of a sample of the same G10 specimen. Single laser pulses were applied at different locations on the specimen surface. Laser pulse durations of 1 millisecond were applied. The laser spot diameter is 3 mm. Incident pulse energies at the surface were measured to be in the range of 0.05 to 0.41 Joule per square millimeter.

The armature is made of 7076-T6 aluminum. In the HEMCL system, the armature dimensions accommodate a rectangular bore of approximately 4.5cm height (also rail height) and 6.5 cm width. The armature has a 1.0 cm wide cutout oriented along the bore axis. The armature is attached to a Lexan cube which serves as a bore rider at the front of the armature.

Specimen surfaces were examined using laser scanning confocal microscopy (LSCM), scanning electron microscopy (SEM), and energy dispersive spectroscopy (EDS). LSCM is ideal for imaging the G10 surfaces because the height variations associated with the cross weave pattern of the glass-fiber bundles.

Thermogravimetric analysis (TGA) was also performed on a G10 sample to characterize the thermal degradation process.

Results

Regarding mechanical damage to the insulator from firing of the three shots, delamination of approximately 20 cm^2 of the top layer of the 0.7 meter G10 specimen is observed near the edge closest to the breech (Figure 1). There are several deep scratches adjacent to the delaminated area. There is also general damage that is similar that described in Gee and Persad [1] in the transition region: epoxy degradation and subsequent fiber removal, possibly by gas wash behind the high velocity projectile. There is no other indication of uniform mechanical damage to the insulator surface that would be expected from general mechanical contact with the moving projectile.

LSCM images were recorded for the damaged G10 surface. The entire surface is blackened. Images from the reverse side (unexposed side) of the G10 sample were also recorded for comparison. Figure 2 is an image from the unexposed side of the G10 sample. It shows a typical junction between the raised bundles and the submerged cross bundles. The original surfaces were ground smooth during manufacture so that most of the top surface glass fibers are short fiber segments held together with epoxy binder. Most of the glass fiber segments show some flattened portions from the grinding process before firing. The junction in this image is filled with a large volume of epoxy matrix material. This surface was gently cleaned with an alcohol soaked cotton swab and, unlike the exposed surfaces, no detectable effects of this cleaning were seen in the microscope images.

Figure 3 is an LSCM image of the exposed face of the G10 at approximately the center of the 0.7 meter sample. The sample surface appears roughened which probably accounts for some of the darkened appearance. This image is representative of the entire 0.7 m G10 sample. Figure 4 is an image from an area immediately adjacent to that in Figure 3 after gentle cleaning with an alcohol moistened cotton swab. The polished appearance of the epoxy region between the fiber weave bundles is in stark contrast to that of Figure 3 and to that of the similarly polished area on the unexposed side (Figure 2). The ease with which a high polish is obtained indicates that a major softening of the epoxy has occurred. The entire 0.7 meter sample exhibited this softened feature.

It is known that pyrolysis of glass reinforced composites produces epoxy decomposition products in the form of gases, oils, waxes and chars solid (heavily cross-linked residues) [4]. The nature of the soft, readily polished surface in 3b is consistent with a wax decomposition product, so we will describe it in those terms in the remainder of this report.

Figure 5 is an LSCM image of a G10 sample that was exposed to laser pulse heating. As in the image in Figure 4, gentle cleaning with an alcohol moistened cotton swab produces a high polish on the epoxy regions between the fiber bundles indicating the formation of the same pyrolytic decomposition product (wax) of the epoxy as in the fired specimens.

Figures 6 and 7 are typical examples of glass fiber softening and deformation found within pits that occasionally form at all locations on the surface of the 0.7 meter insulator specimen. The twisting and stretching of the glass fibers and the rounding of fiber tips show that the fibers were heated above the glass transition temperature, Tg, (approximately 700C for E-glass). The tips generally accumulate adherent coating of debris including aluminum and copper.

Figure 8 is an SEM image from the exposed top surface of a fired specimen showing glass softening with the tendency of the glass tips to bend in the direction of projectile motion. Also shown in the lower left corner are layers of liquefied glass that appear to result from a dragging of liquefied glass in the direction of projectile motion over the underlying fibers. This is probably a result of high velocity air flow behind the projectile. All surfaces are covered in debris, including aluminum and copper.

Laser pulsing also produces softening, deformation of fibers, and preferential melting of the glass fiber tips as observed in the fired specimens. See Figure 9. The softened tips exhibit rounding; at incident laser energies of 0.3J/mm^2 and higher, there is obvious heating well above Tg, as indicated by the formation of glass globules (liquification) at the fiber tips. These glass globules are not observed in the fired specimen (Figure 8); the absence of globules in the fired specimen is likely due to the presence of high rate air flow in a railgun.

The blackened surface can be cleaned by brushing with an alcohol moistened cotton swab. The surface fibers and fiber segments are easily removed. The laser pulsed specimens show far less blackening, as expected, because the volume of volatiles from the 3mm diameter spot will be small relative to that expected in railgun firing.

The most severe thermal damage to the insulator is localized at the two edges of the insulator that are immediately adjacent the two Glidcop/steel junctions. These locations are indicated by the arrows in Figure 1. Approximately 2 to 3mm of insulator material is removed all along a 4 to 5 cm length at the insulator corners at these two locations. Again, the damage is clearly thermal as indicated by numerous observations of fiber softening (fiber deformations) and large quantities of epoxy and glass fiber removal. There is a relatively large amount of copper around these sites. The location of this copper (Figure 1) indicates that it originates from melting of the copper rails that back the Glidcop and steel liners.

Thermographic analysis results are shown in Figure 10. The heating rate during these tests is 10C/min. The onset of the degradation process occurs at ~ 380C where rapid weight loss reflects the evolution of volatile degradation products. Thus, the general degradation of epoxy observed over the entire surface indicates that the surface temperature exceeded 380C everywhere.

The frequent observation of glass liquification shows that the surface actually exceeds 700C everywhere.

Figure 11 is a micrograph showing the cross section of the steel liner at the 122 cm location which is approximately 30 cm downbore from the Glidcop/steel joint. So it is located at roughly the center of the 0.7 meter insulator specimen in this study. It shows a steel melt layer of approximately 20 microns thickness with an associated heat affected zone (HAZ) of approximately the same thickness. This damage was produced with a single shot and is typical of the entire steel surface. No edge groove is detectable, presumably because only a single shot was fired. This uniform heating cannot be attributed to joule heating from current flow through the rails and armature because that current is known to be localized at the top and bottom edges of the conductors [2].

Results Summary

Damage initiates just beyond the one meter location and is uniform over the entire length of the 0.7 meter insulator specimen. The exception to this uniformity is the particularly severe, localized thermal erosion of the insulator at the two edges that coincide with the Glidcop/steel junctions. Peak currents were approximately 1.6 MA in these tests.

There is severe general damage to the epoxy over the entire surface due to pyrolysis. There is clear evidence that the glass fibers at the exposed surfaces were heated to temperatures exceeding Tg, the glass transition temperature of E-glass (~700C). Laser pulse heating was shown to duplicate the thermal damage observed in the insulator of the fired gun. This damage included softening and rounding of the glass tips, as well as the formation of glass globules at the fiber tips at laser energies exceeding $0.3 J/mm^2$. Laser pulse heating also produced the same soft waxy epoxy pyrolysis product seen in the fired insulator specimen. Some of the features are similar to those reported by Gee and Persad[1] in the transition region.

Data on the steel liner surface show a similar uniform heating damage over the entire surface of the steel. The relative uniformity of the steel surface melting and heat affected zone is inconsistent with damage from current flow through the conductors because that current is known to be localized at the top and bottom edges of the rails and armatures[2].

Discussion and Summary

The intense uniform thermal damage covering the entire surfaces of the insulator and the steel rails demonstrates that the heat source cannot be related in any way to the resistive heating of the metallic conductors. It is known from earlier studies that even the resistive heating in the conductors is extremely localized at the top and bottom edges of the rails and armatures. Thus, the only sensible interpretation for the severe thermal damage is heating from plasmas that form behind the armature. The same conclusion was drawn in an earlier study of rail liner surface damage [2].

The fact that laser pulse heating duplicates the damage seen in the HEMCL tests is an indication that the damage is caused by intense radiational heating. Laser pulse heating also duplicates the damage to the steel liner [2]. The damage to the insulator is thus consistent with plasma radiation heating while that to the steel liner is attributable to a combination of plasma radiational heating and resistive heating via parasitic current flow through the plasma.

The exception to uniform damage occurs at the two insulator edges at the liner junctions where the thermal damage is particularly severe. This localized damage is evidently associated with the presence of the Glidcop/steel junction and the associated vaporization of the copper rail beneath the liners. It is unclear whether an existing plasma is locally enhanced by the copper volatiles to create the severe damage or whether a plasma is initiated by the combination of high fields and copper volatiles at the junction.

It is concluded in the earlier study of steel damage in the HEMCL tests [2] that the plasma initiates somewhere near the joint and persists along the remaining length of the 4 meter HEMCL railgun. An important fact is that there is no detectable damage to the lower melting point Glidcop (copper composite) which is on the breech side of the joint. The Glidcop experiences the same current as the steel and is as heavily coated as the steel with molten aluminum from the armature. So the observed damage cannot be attributed to current flow through the conductors or to the deposition of metal droplets, as is sometimes suggested.

Acknowledgements

Thanks are due to Dr. Mark Crawford for supplying the G10 sample.

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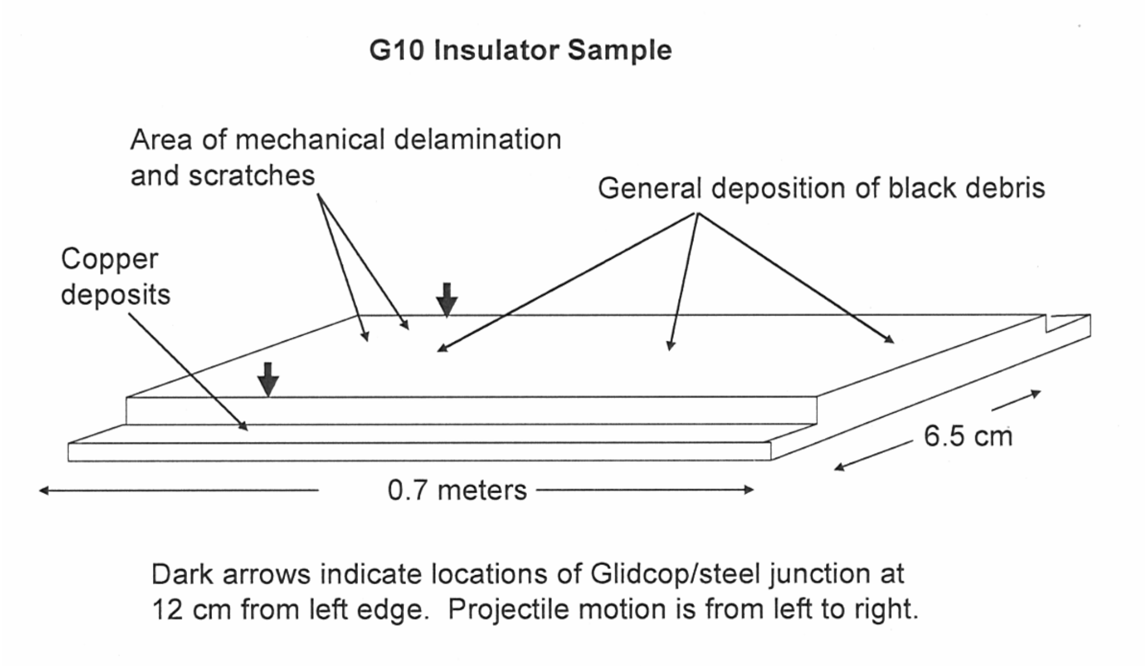

Figure 1. Schematic of G10 insulator specimen.

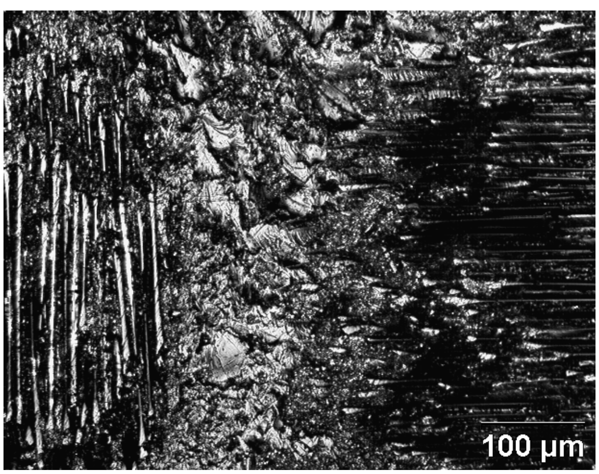

Figure 2. Micrograph of epoxy morphology and fiber bundles of G10 in the as-fabricated condition. Surface was cleaned with alcohol moistened cotton swab.

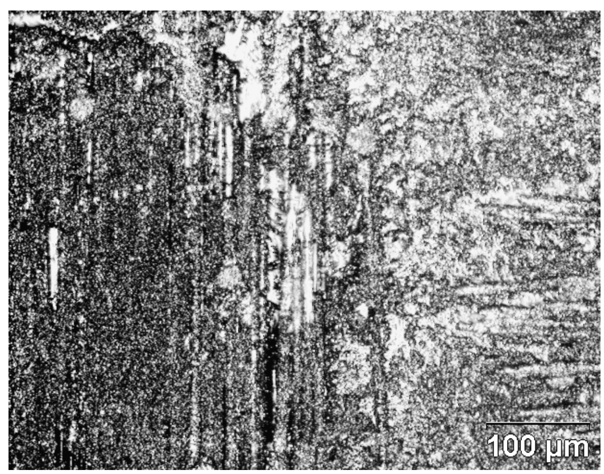

Figure 3. Micrograph of G10 surface exposed to firing conditions (three shots).

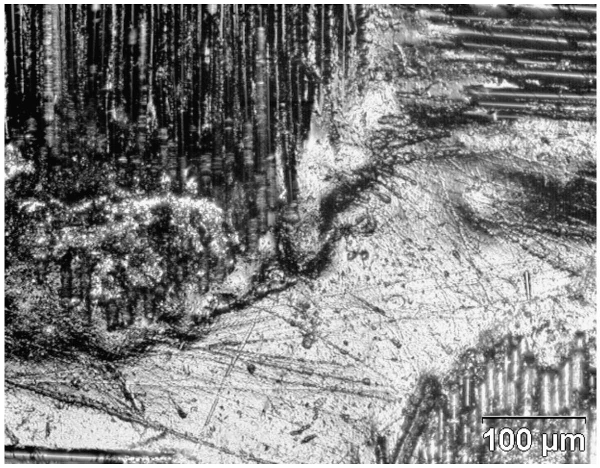

Figure 4. Micrograph of exposed G10 surface after gentle cleaning with an alcohol moistened cotton swab.

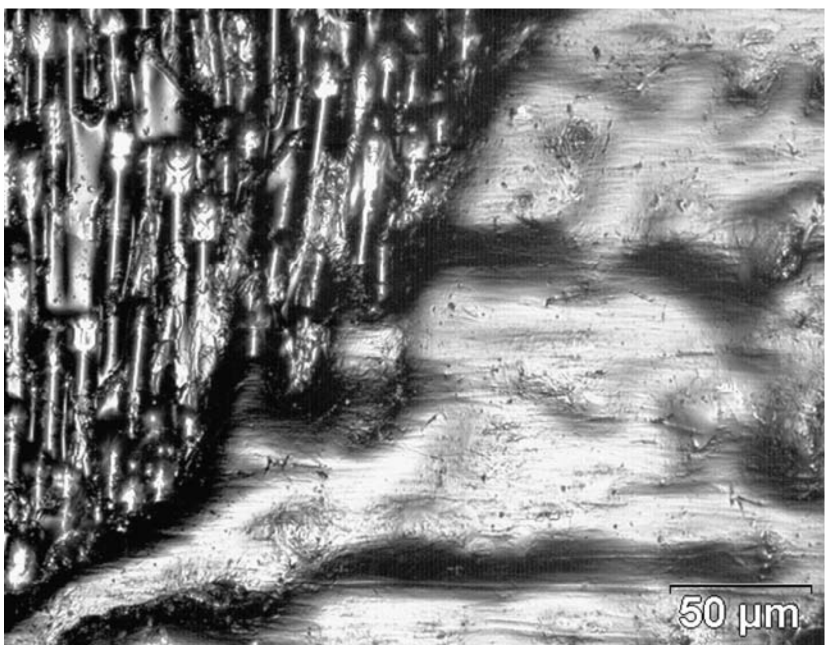

Figure 5. Micrograph of G10 after laser pulsing and cleaning with a cotton swab.

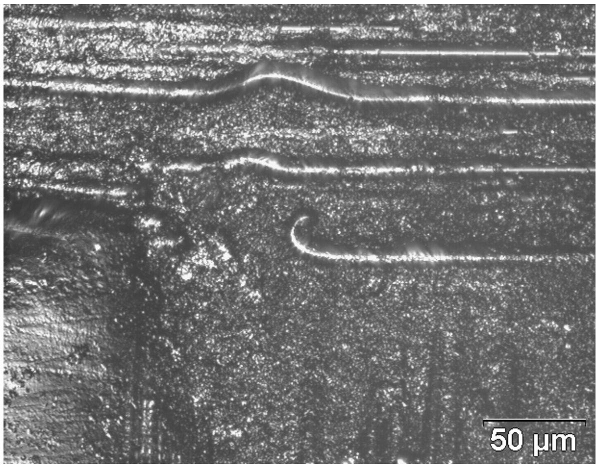

Figure 6. Micrograph showing glass fiber damage in a pit on the G10 surface exposed to firing of three shots.

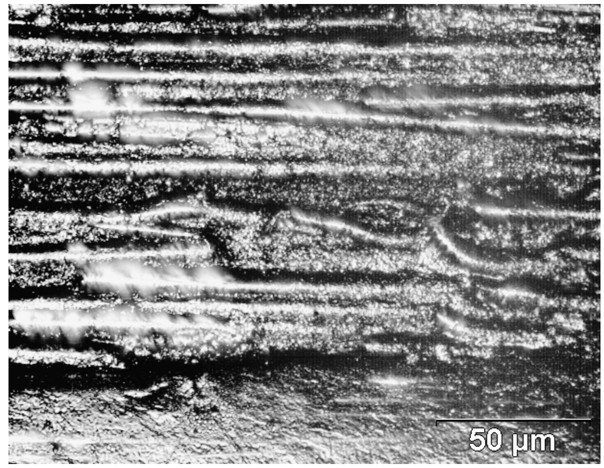

Figure 7. Another micrograph showing glass fiber damage in a pit on the G10 surface exposed to firing of three shots.

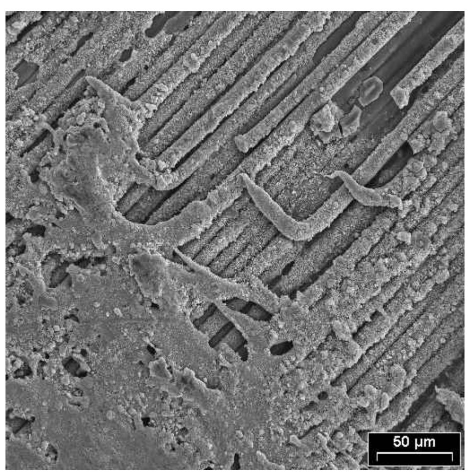

Figure 8. Scanning electron microscope image of glass fibers on the top surface of the G10 exposed to three shots. EDAX shows all surfaces are uniformly coated with a thin layer of debris containing aluminum and copper.

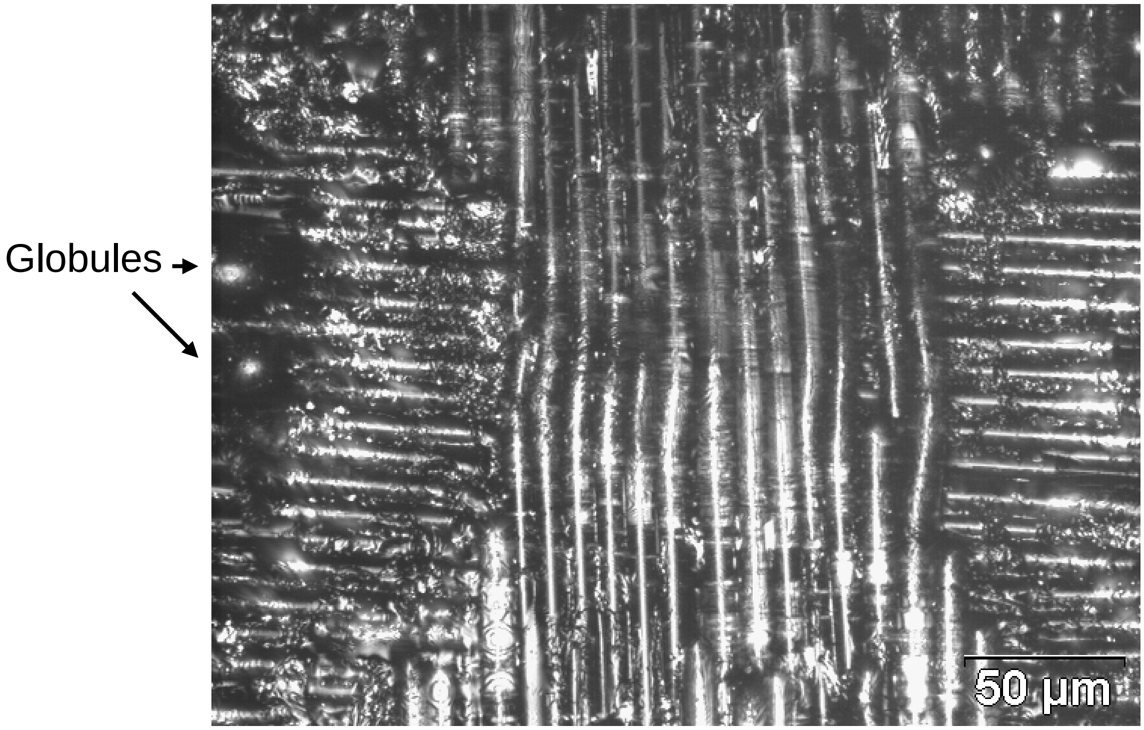

Figure 9. Micrograph of G10 insulator surface exposed to laser pulse heating of 0.3 J/mm^2. Note softening and deformation of glass fibers and the formation of glass globules as a result of liquification of the fiber tips.

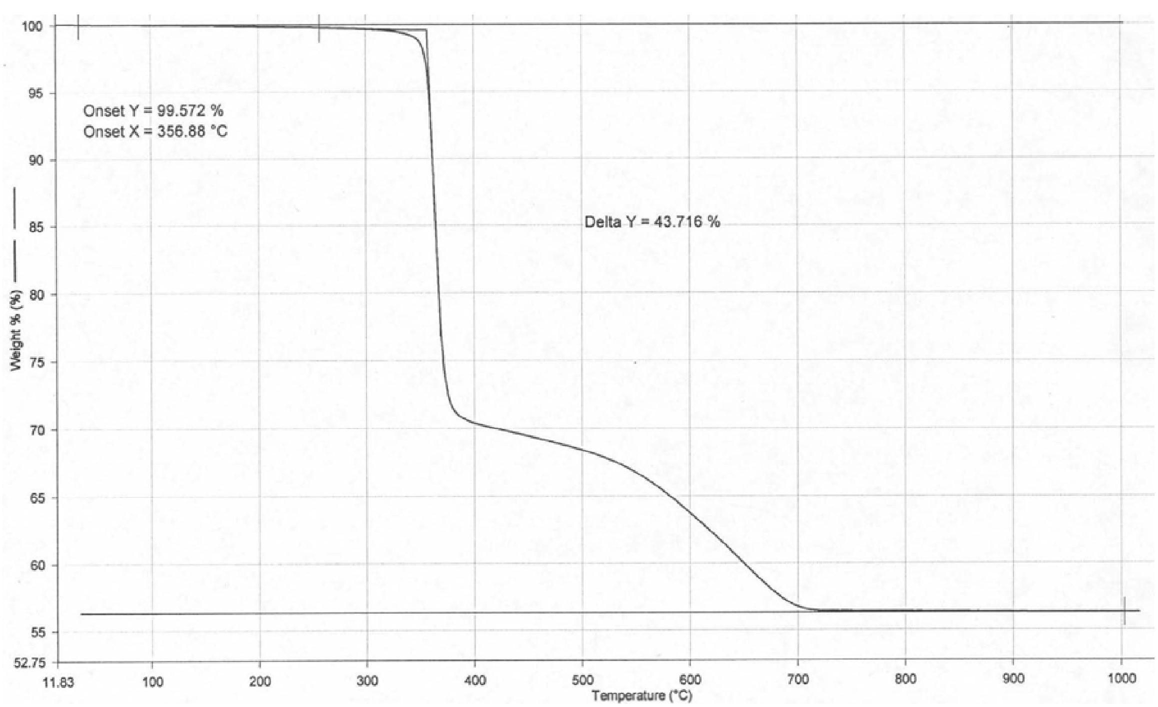

Figure 10. TGA results illustrating the onset of epoxy degradation at approximately 360C.

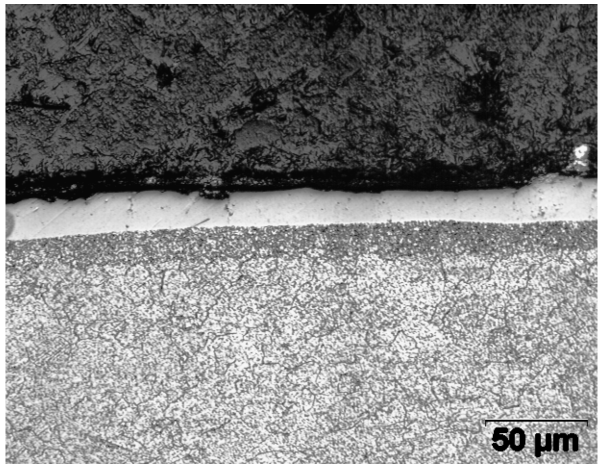

Figure 11. Micrograph showing typical severe thermal damage to the surface of the steel liner adjacent to the 0.7 meter insulator specimen. This damage resulted from a single shot of the HEMCL railgun.